A possibility to determine the P-parity of the Θ^+ pentaquark in the $pn \to \Lambda^0\Theta^+$ reaction

Yu.N. Uzikov [a] [1]

[a] *Joint Institute for Nuclear Research, LNP, 141980 Dubna, Moscow Region, Russia*

Abstract

Spin structure of the reaction $\vec{p}\vec{n} \to \vec{\Lambda}^0\vec{\Theta}$ is analyzed at the threshold in a model independent way under assumption that the Θ^+ is an isosinglet. We found that the sign of the spin-spin correlation parameter $C_{x,x}$ being measured in a double-spin experiment, determines the P-parity of the Θ^+ unambiguously. Furthermore we show that the polarization coefficients K_x^x, K_y^y and K_z^z which describe the polarization transfer from polarized beam or target to the final Λ^0 and Θ^+ are nonzero for a positive parity of the Θ^+ and equal zero for a negative parity. It allows one to determine the P-parity of the Θ^+ in a single-spin measurement, since the polarization of the Λ^0 can be measured via its decay $\Lambda^0 \to \pi^- + p$.

Key words: Pentaquark, strangeness, spin observables
PACS: 13.75.Cs, 14.20-c

[1] E-mail address: uzikov@nusun.jinr.ru

Preprint submitted to Elsevier Science *1 February 2008*

The recent experimental discovery of an exotic barion with a positive strangeness $S = +1$ and surprisingly narrow width [1,2,3,4,5,6], called now as the $\Theta^+(1540)$, stimulated many theoretical works concerning its structure. The quantum numbers of this barion such as spin, parity and isospin are not yet determined experimentally. According to the original prediction within the chiral soliton model [7], the pentaquark Θ^+ belongs to the anti-decuplet with all members having one the same spin-parity, namely $J^P = \frac{1}{2}^+$. From the point of view of constituent quark model the minimal number of quarks in the Θ^+ is five, i.e. the quark content of this barion is $uudd\bar{s}$. Within the naive picture with noninteracting quarks, the ground state of the Θ^+ is expected to be the S-state, therefore the P-parity of the Θ^+ has to be negative, $P = -1$. Inclusion of the special type of qq-interaction into the quark model could lead to the positive parity [8,9]. Diquark model [10] predicts also $P = +1$. On the other hand, the Lattice QCD calculation [11] predict for this barion $P = -1$. Therefore, for quark dynamics the P-parity of the Θ^+ is a key point and it has to be determined experimentally.

Several methods depending on the dynamical assumptions where suggested for determination of the P-parity of the Θ^+ [12]. According to general theorem [13], in order to determine the parity of one particle in a binary reaction $1+2 \to 3+4$ one has to know polarizations at least of two fermions participating in this reaction. Model independent methods for determination of the P-parity of the Θ^+ were suggested recently in Ref. [14] and more detail in Ref. [15] for pp-collision and in Ref.[16] for photoproduction of the Θ^+. The method of Refs.[14,15] is based on measurement of the spin-spin correlation parameter in the reaction $\vec{p}\vec{p} \to \Sigma^+\theta^+$ near the threshold. We show here that the reactions $\vec{p}\vec{n} \to \Lambda^0\Theta^+$ and $\vec{p}n \to \vec{\Lambda}^0\Theta^+$ can be also used for the P-parity determination in a model-independent way under assumption that the isospin of the Θ^+ is known. We assume conservation of the P-parity, total angular momentum and isospin in the reaction and use the generalized Pauli principle for nucleons. We assume here that Θ^+ is an isosinglet, since the isospin partner Θ^{++} was not observed in γp interaction [5,4]. At last, we assume that the spin of the

Θ^+ is $\frac{1}{2}$. Some remarks related to the isospin T=1 and spin $J = \frac{3}{2}$ for the Θ^+ are given at the end of the paper.

Under assumption that the Θ^+ is an isosinglet, the total isospin of the initial pn state equals zero in the rection $pn \to \Lambda^0\Theta^+$. Furthermore, according to generalized Pauli principle, the orbital momentum L of the pn system is even for the spin triplet state S=1 and odd for the singlet state, S=0. We consider here the threshold region with an excess energy less than few tens MeV. At this condition the S-wave dominates in the final state [15,17]. Using P-parity and total angular momentum conservation, one can find that for $P = -1$ of the Θ^+ there is only one transition, i.e. ${}^1P_1 \to {}^3S_1$ and for $P = +1$ there is only the ${}^3S_1 - {}^3D_1 \to {}^3S_1$ transition. We discuss these transitions below separately.

Negative parity. In nonrelativistic formalism, the matrix element for the ${}^1P_1 \to^3 S_1$ transition can be written as

$$F = (\mathbf{T}' \cdot \mathbf{k}) S\, f, \tag{1}$$

where f is a complex amplitude, $\mathbf{T}' = i(\chi^+_{\sigma_3}\, \boldsymbol{\sigma}\sigma_y\, \chi^{(T)+}_{\sigma_4})$, $S = -i(\chi^T_{\sigma_2}\, \sigma_y\, \chi_{\sigma_1})$, $\boldsymbol{\sigma}$ is the Pauli spin matrix, χ_{σ_j} is the Pauli spinor for the j-th particle with the spin projection σ_j, and $\mathbf{k}$ is the unit vector along the beam direction. The polarized cross section for this transition is

$$d\sigma^{neg}(\mathbf{p}_1, \mathbf{p}_2) = d\sigma_0^{neg}(1 - \mathbf{p}_1 \cdot \mathbf{p}_2), \tag{2}$$

where $\mathbf{p}_j$ is the polarization of the beam or target ($j = 1, 2$), $d\sigma_0^{neg}$ is the unpolarized cross section. Below we use for spin-observables the notations defined in [18] and assume that the OZ axis is directed along the vector $\mathbf{k}$. As can be seen from Eq. (2), the spin-spin correlation parameters in the initial state equal to -1: $C_{xx} = C_{yy} = C_{zz} = -1$. We can show using Eq. (1) that the spin transfer coefficients are zeros, $K_j^i = 0$, $(i, j = x, y, z)$.

Positive parity. The only matrix element for this case, ${}^3S_1 - {}^3D_1 \to {}^3S_1$,

can be written as

$$F = G\,(\mathbf{T}' \cdot \mathbf{T}) + (\mathbf{T}' \cdot \mathbf{k})(\mathbf{T} \cdot \mathbf{k})\,F, \tag{3}$$

where $\mathbf{T} = -i(\chi_{\sigma_2}^T \sigma_y \,\boldsymbol{\sigma}\, \chi_{\sigma_1})$ and G and F are complex amplitudes. This amplitudes can be written also as $G = U - W/\sqrt{2}$, $F = 3/\sqrt{2}\,W$, where U and W are the S- and D-waves, respectively, (see, for example, [19]) in the initial state. For polarized beam and target, the cross section takes the following form

$$d\sigma^{pos}(\mathbf{p}_1, \mathbf{p}_2) = d\sigma_0^{pos}\left\{1 + A(\mathbf{p}_1 \cdot \mathbf{p}_2) + B(\mathbf{k} \cdot \mathbf{p}_1)(\mathbf{k} \cdot \mathbf{p}_2)\right\}. \tag{4}$$

Here $d\sigma_0^{pos}$ is the spin-averaged cross section, which can be written as

$$d\sigma_0^{pos} = \frac{1}{4}K\,\left\{|G+F|^2 + 2|G|^2\right\}, \tag{5}$$

where K is the kinematical factor. The factors A and B in Eq.(4) have a form

$$A = \frac{|G+F|^2}{|G+F|^2 + 2|G|^2}, \tag{6}$$

$$B = -2\frac{|F|^2 + 2ReGF^*}{|G+F|^2 + 2|G|^2}. \tag{7}$$

One can see from Eq.(4) that non-zero spin-spin correlation parameters are the following

$$C_{x,x} = C_{y,y} = A, \tag{8}$$

$$C_{z,z} = A + B = \frac{|G-F|^2 - 2|F|^2}{|G+F|^2 + 2|G|^2}. \tag{9}$$

As it follows from Eqs. (6,8), the coefficients $C_{x,x}$ and $C_{y,y}$ are positive for $P = +1$. On the other hand, these observables are negative and maximal in absolute value for $P = -1$ (see Eq.(2)). This result does not depend on the mechanism of the reaction and therefore allows one to determine the P-parity unambiguously in double-spin measurements with transversely polarized beam and target. This result is similar to that found recently for the spin-spin correlation in the reaction $\vec{p}\vec{p} \to \Sigma^+\theta^+$ near threshold [14,15]. The sign of the

coefficient $C_{z,z}$ given by Eq.(9) can be positive or negative for $P = +1$, depending on the relative weight of the S- and D- waves in this transition.

Furthermore, in case of $P = +1$ we found the spin transfer coefficients as

$$\begin{aligned} K_x^x = K_y^y &= 2\frac{|G|^2 + ReGF^*}{|G+F|^2 + 2|G|^2}, \\ K_z^z &= 2\frac{|G|^2}{|G+F|^2 + 2|G|^2}, \\ K_x^y = K_x^z = K_y^x = K_y^z &= K_z^x = K_z^y = 0. \end{aligned} \tag{10}$$

At last, we can show that for unpolarized beam (or target), the polarization of the final particles is zero in the reaction $pn \to \Lambda^0\Theta^+$ independently on the sign of the P-parity of the Θ^+ and the analyzing power is zero also.

As follows from Eqs. (10), for polarized beam (or target) the final particle is polarized along the direction of the initial polarization vector, if the P-parity of the Θ^+ is positive. The sign and the absolute value of the spin-transfer coefficients depends on the relative strength of the S- and D-component and therefore can not be calculated without further dynamical assumptions. For the negative parity $P = -1$ of the Θ^+ the polarization transfer from the beam (or target) to the final particle is zero. Therefore, a measurement of the polarization of one final particle in the reactions $\vec{p}n \to \Lambda^0 + \Theta^+$ or $p\vec{n} \to \Lambda^0 + \Theta^+$ is equivalent to determination of the P-parity of the Θ^+ in a largely model-independent way [2]. The polarization of the final Θ^+ is hardly be measured, but a measurement of the polarization of the Λ^0 is possible by measurement of the angular distribution in the decay $\Lambda^0 \to \pi^- + p$. Indeed, due to P-parity violation in this decay, there is a large asymmetry in angular distribution of final particles in the c.m.s. of the Λ^0 in respect of the direction of the Λ^0 spin. At some experimental conditions a such single-spin experiment is, probably, more simple than the double-spin measurement in the $\vec{p}\vec{p} \to \Sigma^+\Theta^+$ or $\vec{p}\vec{n} \to \Lambda^0\Theta^+$ reactions. At present, a such measurement is possible at COSY

[2] We assume here that there is no cancellation between the S- and D-waves ($U \neq W/\sqrt{2}$) at the threshold of this reaction and therefore $G \neq 0$.

in reaction $\vec{p}d \to \Lambda^0 + \Theta^+ + p_{sp}$ with polarized proton beam and unpolarized deuteron target in a region of quasi-free $\vec{p}n$ interaction. At low momenta of the spectator proton p_{sp} less than ≈ 50MeV/c, the excess energy in the reaction $pn \to \Lambda^0\Theta^+$ is less than 50 MeV that provides the S-wave dominance in the final state [15,17]. Furthermore, as known from study of the $d(p, 2p)n$ reaction [20], an influence of initial and final state interactions on spin observables is rather weak in quasi-free region.

Let us make some further remarks. (i) Since the polarization of the Σ^+ is also self-analyzing via its decays $\Sigma^+ \to p + \pi^0$ or $\Sigma^+ \to n + \pi^+$, we discuss here briefly the polarization transfer in the reaction $\vec{p}p \to \vec{\Sigma}^+\Theta^+$. It is easy to show that for $P = +1$ there is no polarization transfer in this reaction, since the spin-singlet transition ${}^1S_0 \to {}^1S_0$ dominates: $K_i^j = 0$, $(i, j = x, y, z)$. For $P = -1$ there are here two transition amplitudes [14]: ${}^3P_0 \to {}^1S_0$ and ${}^3P_1 \to {}^3S_1$ We found, that the polarization transfer is zero for the first transition. For the spin-triplet transition ${}^3P_1 \to^3 S_1$ the polarization transfer is given by the coefficient $K_z^z = +1$, whereas all others coefficients K_i^j are zero. Due to mixing of these two transitions the total K_z^z can be changed but not vanished, on the whole, $K_z^z \neq 0$. Therefore, a measurement of the longitudinal polarization of the Σ^+ in the reaction $\vec{p}p \to \vec{\Sigma}^+\Theta^+$ with longitudinally polarized beam can be used as a filter for the P-parity of the Θ^+.

(ii) We can show also that for polarized beam (or target) there are spin-spin correlations in the final state of the reaction $pn \to \Lambda^0\Theta^+$ for $P = +1$ and no correlations for $P = -1$. However, we do not discuss these effects in this note, because to observe them experimentally one has to measure polarizations of the Λ^0 and Θ^+ simultaneously that seems unlikely at present.

(iii) **If the isospin of the Θ^+ is equal to 1**, then the total isospin of the initial pn system is $I = 1$ in the reaction $pn \to \Lambda^0\Theta^+$. In this case one has the same transition amplitudes and, therefore, *the same spin observables as in the reaction $pp \to \Sigma^+\Theta^+$*. As follows from Refs. [14,15] and above discussion, the spin observables in the reaction $pp \to \Sigma^+\Theta^+$ are essentially different as

compared to the reaction $pn \to \Lambda^0\Theta^+$ (with the isosinglet Θ^+), namely: $C_{x,x} = -1$ and $K_i^j = 0$ $(i,j = x,y,z)$ for $P = +1$, whereas the $C_{x,x}$ is nonnegative [15] and $K_z^z \neq 0$, if $P = -1$. On the contrary, the spin observables of the reaction $\vec{p}\vec{p} \to \Sigma^+\Theta^+$ are not sensitive to the isospin of the Θ^+, when it takes the possible values $0, 1$ or 2. Obviously, the reaction $pn \to \Lambda^0\Theta^+$ is forbidden for the isospin $T = 2$ of the Θ^+ due to isospin invariance of strong interactions.

(iv) In chiral models (see, for example, [9]), the $\Theta^+(\frac{1}{2}^P)$ could have a partner with the spin $J = \frac{3}{2}$. For the spin $\frac{3}{2}$ of the Θ^+, at the threshold of the reaction $pp \to \Sigma^+\Theta^+$ there is one transition ${}^1D_2 \to {}^5S_2$ for $P = +1$ and two transitions ${}^3P_1 \to {}^3S_1$ and ${}^3P_2 - {}^3F_2 \to {}^5S_2$ for $P = -1$. Since for $P = +1$ there is only one amplitude with the spin-siglet initial state, one has got for this case $C_{x,x} = C_{y,y} = C_{z,z} = -1$. For $P = -1$, the initial state is the spin-triplet, therefore one should expect that $C_{x,x}$ is nonnegative, $0 \leq C_{x,x} \leq +1$. In the reaction $pn \to \Lambda^0\Theta^+$ with the spin $J = \frac{3}{2}$ of the Θ^+, we have the same transitions as for $J = \frac{1}{2}$, but only in the case of $P = +1$ one new transition, ${}^3D_2 \to {}^5D_2$, contributes in addition to the ${}^3S_1 - {}^3D_1 \to {}^3S_1$ transition. Since the all transitions for $P = +1$ are the spin-triplet ones in the pn initial state, one should expect that the spin-spin correlation parameter $C_{x,x}$ is still nonnegative for $P = +1$, whereas for $P = -1$ we found $C_{x,x} = C_{y,y} = C_{z,z} = -1$. Therefore, in both these reactions, $pp-$ and $pn-$, the sign of the spin-spin correlation parameter $C_{x,x}$ allows one to determine the P-parity of the Θ^+ unambiguously for both cases $J = \frac{1}{2}$ and $J = \frac{3}{2}$. A question about the polarization transfer coefficients for $J = \frac{3}{2}$ is more complicated and will be studied separately.

In conclusion, assuming that the Θ^+ is the isosinglet with the spin $\frac{1}{2}$, we have analyzed in a model independent way the spin-spin correlation parameters $C_{i,j}$ and spin-transfer coefficients K_i^j of the reaction $pn \to \Lambda^0\Theta^+$ near the threshold. We found that the P-parity of the Θ^+ can be measured in a single spin experiment with the transversally or longitudinally polarized beam or target if the polarization of the final Λ^0 is measured via the decay $\Lambda^0 \to \pi^- + p$.

A similar result is found here for the $\vec{p}p \to \vec{\Sigma}^+\Theta^+$ with the longitudinally polarized beam. In contrast to the reaction $p\,p \to \Sigma^+\Theta^+$, in the reaction $p\,n \to \Lambda^0\Theta^+$ the sign of $C_{x,x}$ coincides with the sign of the P-parity of the Θ^+ and the non-zero polarization transfer occurs only for $P = +1$. However, if the Θ^+ is an isotriplet, the spin observables of the reaction $pn \to \Lambda^0\Theta^+$ are identical with those for the reaction $pp \to \Sigma^+\Theta^+$. Therefore a measurement of the above spin observables in these two reactions allows one to determine both the P-parity and isospin of the Θ^+.

References

[1] T. Nakano *et al.*, Phys. Rev. Lett. **91** (2003) 012002.

[2] V. V. Barmin *et al.*, Phys. Atom. Nucl. **66** (2003) 1715.

[3] S. Stepanyan *et al.*, Phys. Rev. Lett. **91** (2003) 252001.

[4] V. Kubarovsky et al., Phys. Rev. Lett. **92** (2004) 32001.

[5] J. Barth et al., Phys. Lett. B **572** (2003) 127.

[6] A. Aleev et al., arXiv:hep-exp/0401024.

[7] D. Diakonov, V. Petrov and M. Polyakov, Z. Phys. A359, 305-314 (1997).

[8] A. Hosaka, Phys. Lett. **B 571** (2003) 55.

[9] L.Ya. Glozman, Phys. Lett. **B 575** (2003) 18.

[10] R.L. Jaffe and F. Wilchek, Phys. Rev. Lett. **91** (2003) 232003.

[11] F. Csikor, Z. Fodor, S.D. Katz, T.G. Kovacs, hep-lat/0309090. Shoichi Sasaki, hep-lat/0310014.

[12] T. Hyodo, A. Hosaka and E. Oset, nucl-th/0307105; S.I. Nam, A. Hosaka and H.-Ch. Kim, hep-ph/0308313; Y. Oh, H. Kim and S.H. Lee, hep-ph/0310019; Q. Zhao, hep-ph/0310350; K. Nakayama and K. Tsushima, hep-ph/0311112; Q. Zhao, J.S. Al-Khalili, hep-ph 0312348.

[13] P.L. Csonka, M.J. Moravchik, M.D. Scandor, Phys. Rev. Lett. **15** (1965) 353.

[14] A. Thomas, K. Hicks, A. Hosaka, hep-ph/0312083.

[15] Ch. Hanhart et al., hep-ph/0312236.

[16] M. Rekalo and E. Tomasi-Gustafsson, hep-ph/0401050.

[17] S.I. Nam, A. Hosaka and H.-Ch. Kim, hep-ph/0401074.

[18] G.G. Ohlsen, Rep.Prog.Phys. **35** (1972) 717.

[19] G.D. Alkhazov, V.V. Anisovich, P.E. Volkovitskiy. “Diffracionnoe vzaimodeistvie adronov s yadrami pri visokih energiyah”, Leningrad, Nauka, 1991 (in Russian).

[20] V. Punjabi et al., Phys. Rev. **C 39** (1989) 608.